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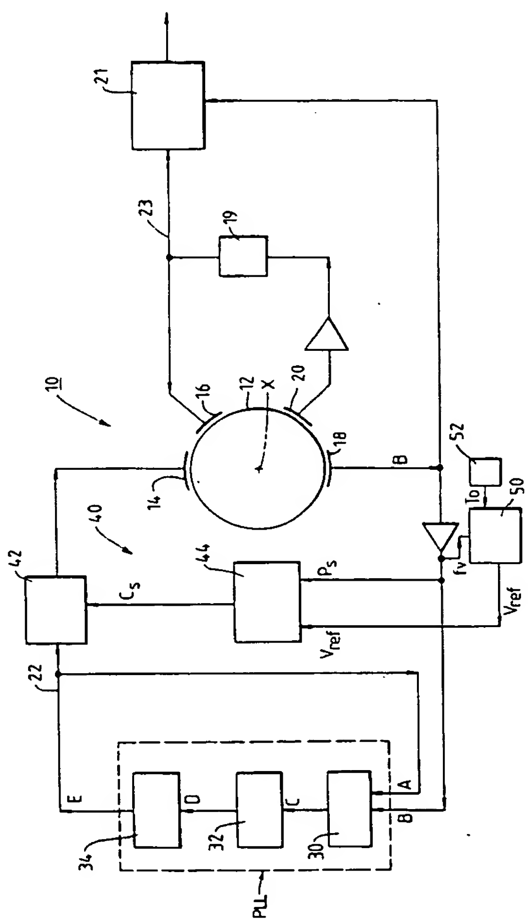
(54) Method of and apparatus for compensating for material instabilities in piezoelectric materials.

(57) The vibrating rate sensor (10) for detecting rotational movement about an axis (X) is provided with means for measuring the resonant frequency of the cylinder (12) and the operating temperature and means for compensating for temperature and ageing instabilities within the piezoelectric materials incorporated in the cylinder (12).

Fig. 5.



EP 0 592 171 A1

The present invention relates to a method of and apparatus for compensating for material instabilities in piezoelectric materials and relates particularly, but not exclusively, to compensation for "ageing" in rotation rate sensors utilising Lead Zirconate Titanate (PZT).

Figure 1 is a system diagram for a conventional single axis rate sensor of the type described in GB2061502 to R M Langdon and GB 2154739 to J S Burdess. The cylinder is driven into resonance by applying an oscillating electric signal to the drive transducers. The vibration pattern, viewed from the top, of the resonant mode is shown in Figure 2. It will be seen that there are anti-nodes of maximum radial vibration and nodes of minimum radial vibration present. The primary loop control maintains this resonance by ensuring a 90 degree phase shift between the primary drive transducer and primary pick-off transducer. When the rate sensor is rotated, the resonant mode rotates with respect to the cylinder, and a signal can be detected on the secondary pick-off transducer. This signal is amplified and fed back to the secondary drive transducer in order to null it to zero. The strength of the nulling signal is proportional to rotation rate. The signal is demodulated and outputted as a dc. rate signal.

It should be noted that the vibration pattern can have a different shape to that shown in Figure 2. However, the vibration pattern must have nodes and anti-nodes occurring cylindrically around the perimeter of the cylinder. The cylinder does not have to be driven exactly at resonance - but in practice it is desirable so to do. The resonant body neither has to be circular, nor cylindrical, indeed hemispheres and rings can be used. However, it is desirable that the oscillating modes seen by primary and secondary electronic circuits (referred to as the primary and secondary resonances) have the same, or nearly the same, resonant frequency.

GB2061502 discloses a metal conventional cylinder 12, closed at one end and supported by a stem, which is driven into resonance using piezoelectric elements stuck onto the metal cylinder as shown in Figure 3. Piezoelectric elements are also used to pick-off the movements.

GB 2154739 describes a similar conventional device of unitary construction made from piezoelectric material where the drive and pick-off transducers are formed by polarising the material between electrodes regions as shown in Figure 4. The device includes two charge amplifiers A_1 and A_2 an oscillator circuit and active gain control system OC, and a feed back system FB.

Both the above mentioned patents describe similar electronic circuits to that shown in Figure 1. From Figure 1, it can be seen that the phase locked loop PLL comprises a phase detector PD, low pass filter F and a voltage controlled oscillator VCO. The VCO output is connected to both the primary drive electrode G via a gain control element H and the reference input on the phase detector PD.

The characteristics of the phase detector PD is that it outputs a signal C which is proportional to the phase difference between the signals A and B at its inputs. The phase detector PD used here has Zero output when the inputs are in quadrature, i.e.: it is a quadrature phase detector.

When the primary loop PL is locked, the phase detector PD input signals A and B are in quadrature, and thus the cylinder 12 is on resonance. If the phase of the signal at B alters, this is sensed by the phase detector, which outputs a correction signal C which is filtered and used to control the phase of the VCO signal.

Unfortunately, piezoelectric materials such as PZT have a large change in their quality factor Q over temperature. This implies that the amplitude of the resonant mode for constant primary drive signal will vary proportionally to Q and will therefore vary with temperature.

The system in Figure 1 avoids the above mentioned problem by utilising a gain control circuit in the primary loop PL, which compares the amplitude of the primary pick-off signal (B) to an external reference voltage V_{ref} via a controller CL in order to maintain the primary pick - off signal at constant amplitude. This helps to stabilise the dependence of the scale factor of the rate sensor with temperature by reducing the dependence on Q.

A secondary drive transducer 16 and primary and secondary pick-off transducers 18, 20 form part of a secondary loop SL together with a low pass filter 19 and a demodulator 21.

Piezoelectric ceramics contain many small granules, each containing domains in which the electric dipoles are aligned. The grains are randomly orientated, so the net electric dipole is zero - i.e.: the bulk material is not piezoelectric.

The material is made piezoelectric by poling, in which a high electrical field is applied to the material at elevated temperatures. The process aligns the dipoles in the direction of the electric field and the dipoles remain in this direction after the field is removed. Such a technique is disclosed in, for example, ANSI/IEEE std 176-1987 "IEEE standard on Piezoelectricity" and in Cady, W.G. Piezoelectricity, by Dover Publications, New York, 1964.

Unfortunately, most piezoelectric ceramic materials gradually become less piezoelectric with time, that is, they age. It has been found that the ageing process is typically logarithmic with time - the material ages by the same amount in the first day after poling as in the next ten days, and by the same amount in the next one hundred days, and so on.

In addition to ageing, the piezoelectric parameters also display thermal hysteresis. Worse than this,

the parameter values do not necessarily return to the same value after undergoing a temperature cycle. The effect can be characterised by measuring and plotting the parameter variations over temperature cycles, concentrating on the often slow and incomplete recovery of the parameter value with time.

Piezoelectric parameter variations will have a significant effect on rotation rate sensor performance. For example, changes in the piezoelectric properties of the material will vary both the Direct Piezoelectric effect (charge produced when the material is under applied mechanical stress,) and the Reverse Piezoelectric effect (mechanical strain produced under applied electric field). Thus the "effective input and output gains" of devices fabricated from the piezoelectric material will vary.

In addition to the above, if the frequency of parts fabricated from the material, and the capacitance of electrodes vary, then this too can alter the effective input and output gains.

In particular, these parameter variations will cause a change in the scale factor (or sensitivity, i.e.: output signal for a given applied rate of rotation) of the rotation rate sensor.

Further, the scale factor of the rate sensor is also a direct function of the frequency at which the sensing element (i.e.: the cylinder) vibrates. The natural frequency of the cylinder changes with time and temperature owing to material parameter variations. Hence, the rate sensor scale factor will vary as a direct result.

As described above, the rate sensor can be designed with a circuit (Figure 1) to eliminate the variations in scale factor caused by the primary output signal varying with temperature. However, this loop is primarily designed to counteract changes in the Quality Factor Q with temperature and time.

Unfortunately, the loop does not cope with all the variation in piezoelectric parameters. As a result of this, the scale factor of the rate sensor will age with time and display thermal hysteresis. These variations can contribute from 5% to 15% variation for a finished product. These are large variations, especially when attributed to a single source - i.e.: the material.

In summary, rate sensors utilising vibrating cylinders made from piezoelectric material show ageing and thermal instabilities in their properties. These result in unacceptably high variations in the scale factor of the rate sensors. Variations in rate sensors utilising piezoelectric transducers stuck onto metallic vibrating pieceparts (such as described in GB2061302) are predicted to show analogous effects. Variations in other sensors whose sensitivities are dependent on the piezoelectric properties of the material are also predicted to show analogous effects.

There is thus a need to reduce and possibly eliminate the problems of ageing and thermal instabilities in items made from or incorporating piezoelectric materials.

According to one aspect of the present invention there is provided a rate sensor assembly for detecting rotational movement about an axis X including a cylinder incorporating piezoelectric material, which cylinder is positioned about said axis, primary and secondary drive transducers for applying radial vibrations to said cylinder, primary and secondary pick-off transducers for detecting the presence of vibrations induced in said cylinder, a primary control loop for receiving a signal from the primary pick-off transducer and maintaining resonance by generating a ninety degree phase shift between the primary drive transducer and the primary pick-off transducer, and a secondary control loop for receiving a signal from the secondary pick-off transducer indicative of rotation thereof and for directing said signal to the secondary drive transducer so as to null it to zero, characterised by including a temperature sensor for sensing an operating temperature of the cylinder and generating an operating temperature signal (To) and compensation means for receiving the operating temperature signal and the resonant frequency signal from the primary pick-off transducer and using them to compensate for parameter variations in the cylinder piezoelectric material.

Preferably the cylinder piezoelectric material is Lead Zirconate Titanata (PZT) and wherein the parameter variations to be compensated for include ageing.

Conveniently the assembly includes a gain control circuit in the primary control loop, which gain control circuit comprises a gain control device and a first controller operable to compare the amplitude of the primary pick-off signal with a reference voltage (V_{ref}) and apply a correction signal CS to the gain control device.

Advantageously the compensation means includes a second controller operable to receive the operating temperature signal (To) and to monitor the resonant frequency of the cylinder and use them to provide an open loop compensation of the reference amplitude of the primary pick-off amplitude.

Preferably the second controller includes a frequency difference meter operable to provide an output voltage V2 proportional to the difference in the cylinder frequency and the original set value of the cylinder frequency at ambient temperature.

Conveniently assembly includes a gain control device in the primary control loop 22, and wherein the compensation means includes a controller connected between the temperature sensor and the gain control device which controller is operable to monitor the resonant frequency of the cylinder and adjust the input drive amplitude by reference to the frequency and temperature.

Alternatively the control means is a compensation circuit to which the temperature sensor, operating temperature signal (To) and the primary pick-off sig-

nal (B) are outputted.

Advantageously the compensation circuit includes a microprocessor.

Preferably the primary control loop includes a phase locked loop having a phase detector configured to operating at quadrature, a low pass filter and a voltage controlled oscillator.

According to another aspect of the present invention there is provided a method of compensating for parameter variations in piezoelectric material forming at least part of a cylinder of a rate sensor assembly for detecting rotational movement about an axis (X) on which the cylinder is positioned, characterised by the steps of sensing the operating temperature (To) of the cylinder, sensing the resonant frequency (B) of the cylinder, and utilising the sensed temperature (To) and sensed frequency (B) to compensate for said parameter variations.

Preferably the operating temperature (To) and the resonant frequency (B) are fed to a controller which provides open loop compensation of the reference amplitude of the primary pick-off amplitude.

Alternatively the operating temperature (To) and the resonant frequency (B) are fed to a controller which adjusts the input drive amplitude to the cylinder by reference to the frequency (B) and temperature (To).

Conveniently the temperature (To) and the resonant frequency (B) are outputted to a compensation circuit.

The present invention will now be more particularly described by way of example only with reference to the accompanying drawings, in which:

Figure 1 is a conventional schematic diagram for a single-axis rate sensor;

Figure 2 is a diagrammatic representation of the vibration pattern, viewed from the top of the resonant mode of the vibrating portion of the conventional rate sensor shown in Figure 1;

Figure 3 illustrates a conventional vibrating cylinder of the type incorporated in the prior art arrangement and illustrates the electrode position thereon,

Figure 4 illustrates a similar conventional device of unitary construction made from piezoelectric material where the drive and pick-off transducers are formed by polarising the material between electrode regions,

Figures 5 to 8 illustrate schematically a rate sensor according to various different embodiments of the present invention and,

Figure 9 is a block diagram showing one example implementation of the controllers and gain control blocks for the present invention.

Referring now to the Figures 5 to 9 in general, a vibrating rate sensor 10 according to one embodiement of the present invention for detecting rotational movement about an axis includes a cylinder 12 positioned about said axis x, primary and secondary drive transducers 14, 16 for applying radial vibration to said cylinder, primary and secondary pick-off transducers 18,20 for detecting the presence of vibration induced in said cylinder 12 and primary and secondary control loops 22, 23. The primary control loop is provided for receiving a signal from the primary pick-off transducer 18 and for maintaining resonance of the structure by generating a 90 degree phase shift between the primary drive transducer 14 and the primary pick-off transducer 18.

The secondary control loop 23 is provided for receiving a signal from the secondary pick-off transducer 20 which is indicative of rotation of the structure. This signal is directed to the secondary drive transducer so as to null it to zero. The primary control loop 22 may include a phase locked loop (PLL) having a phase detector 30 configured to operate at quadrature, a low pass filter 32 and a voltage controlled oscillator 34. The voltage control oscillator 34 provides an output signal for driving the primary drive transducer 14 and a reference signal (A) for returning to phase detector 30 to form a portion of the phase locked loop. The operation of such primary drive circuits is well known in the art and is therefore not described in further detail herein.

Reference may, however, be made to the above mentioned Patents and also to the Applicants copending British Application No.9207886.4. This arrangement overcomes the problems associated with variations with temperature of the quality factor Q of piezoelectric materials by incorporating a gain control circuit 40 in the primary loop. The circuit 40 comprises a gain control device 42 and a controller 44. The controller compares the amplitude of the primary pick-off signal Ps with a reference voltage V_{ref} and applies a correction signal Cs to the gain control device (42) in order to maintain the primary pick-off signal at constant amplitude. This helps to stabilise the dependence of the scale factor of the rate sensor with temperature.

The present invention includes a temperature sensor (52) for sensing an operating temperature of the cylinder (12) and generating an operating temperature signal To. This signal To is received by a second controller (50) which monitors the resonant frequency of the cylinder and the operating temperature To and uses these to provide an open loop compensation of the reference amplitude of the primary pick-off amplitude.

The second controller (50) combines signals from the temperature sensor (52), a voltage reference source V_{ref} and a measure of the frequency variation fv so as to derive an output signal V4 proportional to the desired primary pick-off amplitude from the cylinder.

The temperature sensor (52) may be any commercially available temperature sensor where the

output voltage V1 is proportional to temperature. For this example, V1 is scaled in volts/°C. The accuracy of the sensor needs to be, typically 2°C. The details of controller (40) and (50) are shown in more detail in Figure 9 in which it will be seen that controller (50) includes a frequency difference meter (56) in the form of a circuit which provides an output voltage V2 proportional to the difference in the cylinder frequency and the original set value of the cylinder frequency at ambient. The controller 44 includes a shaping device (53). For this example, V2 is scaled in Volts Hz. One implementation is to measure the difference in frequencies between an accurate reference frequency F_{ref} and the frequency which is supplied to the gyro. The reference frequency might also be supplied at a lower or higher integer multiple of the cylinder frequency and scale accordingly in the frequency meter (56). The accuracy of the frequency Difference Meter is required to be about 0.2%.

V_{ref} is a reference voltage, possibly derived from a proprietary band gap semiconductor reference. Again, for this example, V_{ref} is 1 volt, and we have $V3 = V_{ref}$.

These signals are combined to give a voltage V4, where:

$$V4 = K1.V1 + K2.V2 + K3.V3 \quad (1)$$

Typical values for the coefficients are:

$K1 = -2 \times 10^{-3}$
$K2 = 5.5 \times 10^{-4}$
$K3 = 1$

It must be stressed that the above implementation is an example only. In practice more convenient scaling of V1, V2 and V3 could be chosen together with corresponding values of K1, K2 and K3.

In addition, there are many ways of practically implementing the controller. However, all these ways will have the common feature in that the resulting equations will be similar to the above.

The purpose of the first controller is to provide a control signal to the gain control element in order to force the primary pick-off amplitude to V4.

One possible implementation is to demodulate the primary pick-off signal with respect to the VCO signal in order to measure the amplitude of the primary pick-off signal. This is then compared with V4, and the error signal fed into a shaping circuit which provides the necessary control signal to the gain control element.

This implementation requires a knowledge of control theory in order to ensure that loop stability and adequate accuracy is obtained. However, a possible implementation is to utilise a very slow integrator in the shaping circuit in order to avoid interaction of this amplitude control loop with the other control loops.

The purpose of the gain control element is to adjust the amplitude of the VCO with respect to the control input from the first controller. Various implementations are possible, however, one possible implementation is to use a commercially available automatic gain control integrated circuit.

The general scheme for a closed - loop scheme is shown in Figure 5.

The general model for an open-loop scheme is shown in Figure 6 where the sensing element is driven into oscillation by an external drive circuit. The drive amplitude is adjusted by reference to the frequency and temperature. The scheme is open loop because the primary pick-off amplitude is not stabilised. Such a sensor will have a predictable variation with temperature arising from Q variations. These could be externally compensated for by measuring the amplitude of the primary pick-off signal.

Figures 7 & 8 show open and closed loop schemes similar to the above, but where the compensation for variations in piezoelectric parameters is carried out externally by, say, a microprocessor (not shown). The algorithms required are well understood in the art and are therefore not described herein.

The basic scheme could be added to any of the combination of arrangements illustrated in the Applicants co-pending application No. 9207886.4

Claims

1 A rate sensor assembly for detecting rotational movement about an axis (X) including a cylinder (12) incorporating piezoelectric material, which cylinder is positioned about said axis, primary and secondary drive transducers (14, 16) for applying radial vibrations to said cylinder (12), primary and secondary pick-off transducers (18, 20) for detecting the presence of vibrations induced in said cylinder, a primary control loop for receiving a signal from the primary pick-off transducer (18) and maintaining resonance by generating a ninety degree phase shift between the primary drive transducer (14), and the primary pick-off transducer (18), and a secondary control loop for receiving a signal from the secondary pick-off transducer (20) indicative of rotation thereof and for directing said signal to the secondary drive transducer (16) so as to null it to zero, characterised by including a temperature sensor (52) for sensing an operating temperature of the cylinder and generating an operating temperature signal (To) and compensation means for receiving the operating temperature signal and the resonant frequency signal from the primary pick-off transducer (18) and using them to compensate for parameter variations in the cylinder piezoelectric material.

2 A rate sensor assembly according to claim 1, wherein the cylinder piezoelectric material is Lead Zirconate Titanate (PZT) and wherein the parameter variations to be compensated for include ageing.

3 A rate sensor assembly according to claim 1 or

claim 2, including a gain control circuit (40) in the primary control loop (22), which gain control circuit (40) comprises a gain control device (42) and a first controller (44) operable to compare the amplitude of the primary pick-off signal with a reference voltage (V_{ref}) and apply a correction signal (CS) to the gain control device (42).

4 A rate sensor assembly according to claim 3, wherein the compensation means includes a second controller (50) operable to receive the operating temperature signal (To) and to monitor the resonant frequency of the cylinder (12), and use them to provide an open loop compensation of the reference amplitude of the primary pick-off amplitude.

5 A rate sensor assembly according to claim 4, wherein the second controller (50) includes a frequency difference meter (56) operable to provide an output voltage V2 proportional to the difference in the cylinder frequency and the original set value of the cylinder frequency at ambient temperature.

6 A rate sensor assembly according to claim 1 or claim 2, including a gain control device (42) in the primary control loop (22), and wherein the compensation means includes a controller (50a) connected between the temperature sensor (52) and the gain control device (42), which controller (51a) is operable to monitor the resonant frequency of the cylinder 12 and adjust the input drive amplitude by reference to the frequency and temperature.

7 A rate sensor assembly according to anyone of claims 1 to 3, wherein the control means is a compensation circuit to which the temperature sensor, operating temperature signal (To) and the primary pick-off signal (B) are outputted.

8 A rate sensor assembly according to claim 7, wherein the compensation circuit includes a microprocessor.

9 A rate sensor assembly according to any one of claims 1 to 8, wherein the primary control loop (22) includes a phase locked loop (PLL) having a phase detector (30) configured to operate at quadrature, a low pass filter (32) and a voltage controlled oscillator (34).

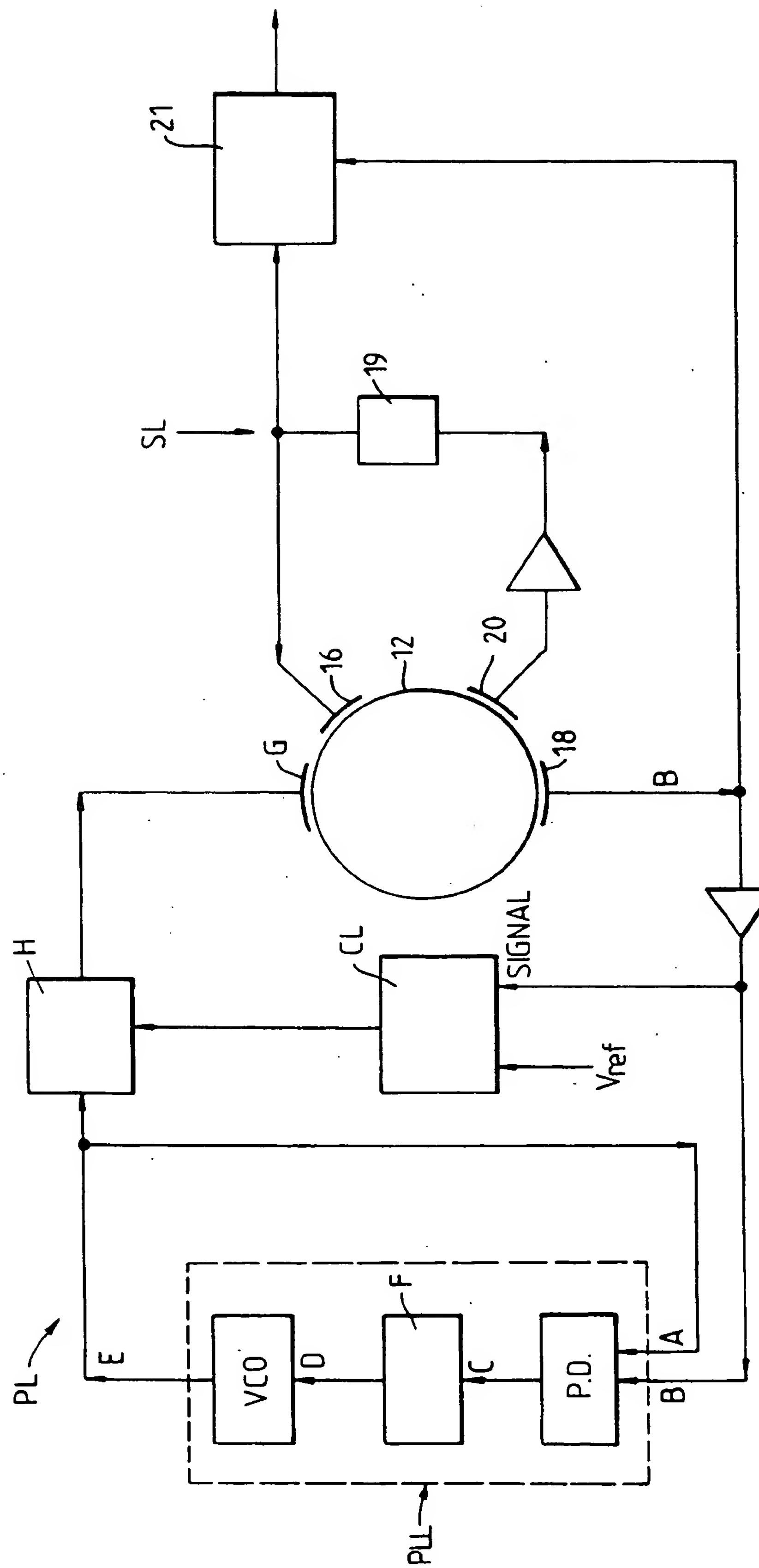
10 A method of compensating for parameter variations in piezoelectric material forming at least part of a cylinder (12) of a rate sensor assembly (10) for detecting rotational movement about an axis (X) on which the cylinder (12) is positioned, characterised by including the steps of sensing the operating temperature (To) of the cylinder (12), sensing the resonant frequency (B) of the cylinder (12), and utilising the sensed temperature (To) and sensed frequency (B) to compensate for said parameter variations.

11 A method according to claim 10, in which the operating temperature (To) and the resonant frequency (B) are fed to a controller (50a) which provides open loop compensation of the reference amplitude of the primary pick-off amplitude.

12 A method according to claim 10, in which the operating temperature (To) and the resonant frequency (B) are fed to a controller (50a) which adjusts the input drive amplitude to the cylinder (12) by reference to the frequency (B) and temperature (To).

13 A method according to claim 10, in which the temperature (To) and the resonant frequency (B) are outputted to a compensation circuit.

Fig. 1



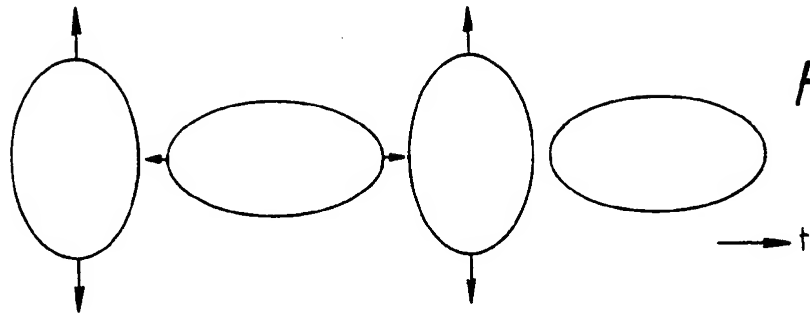


Fig. 2

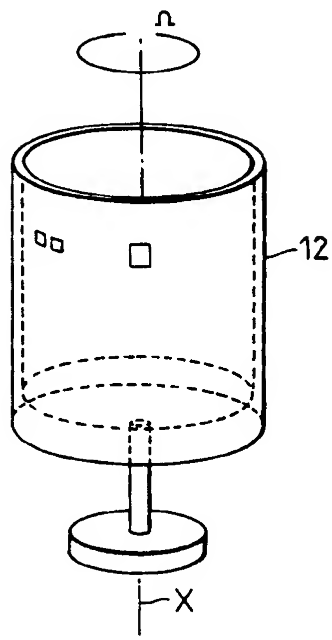


Fig. 3

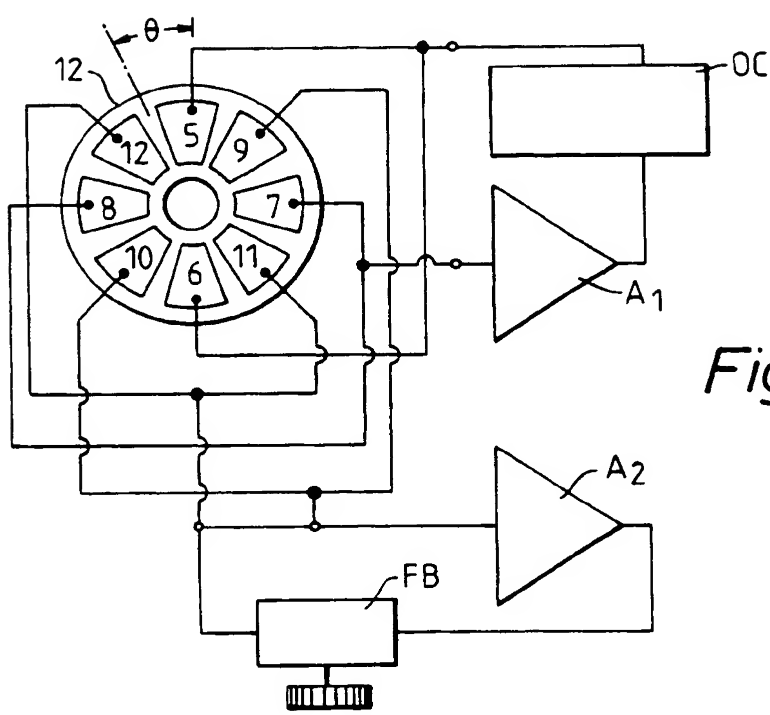
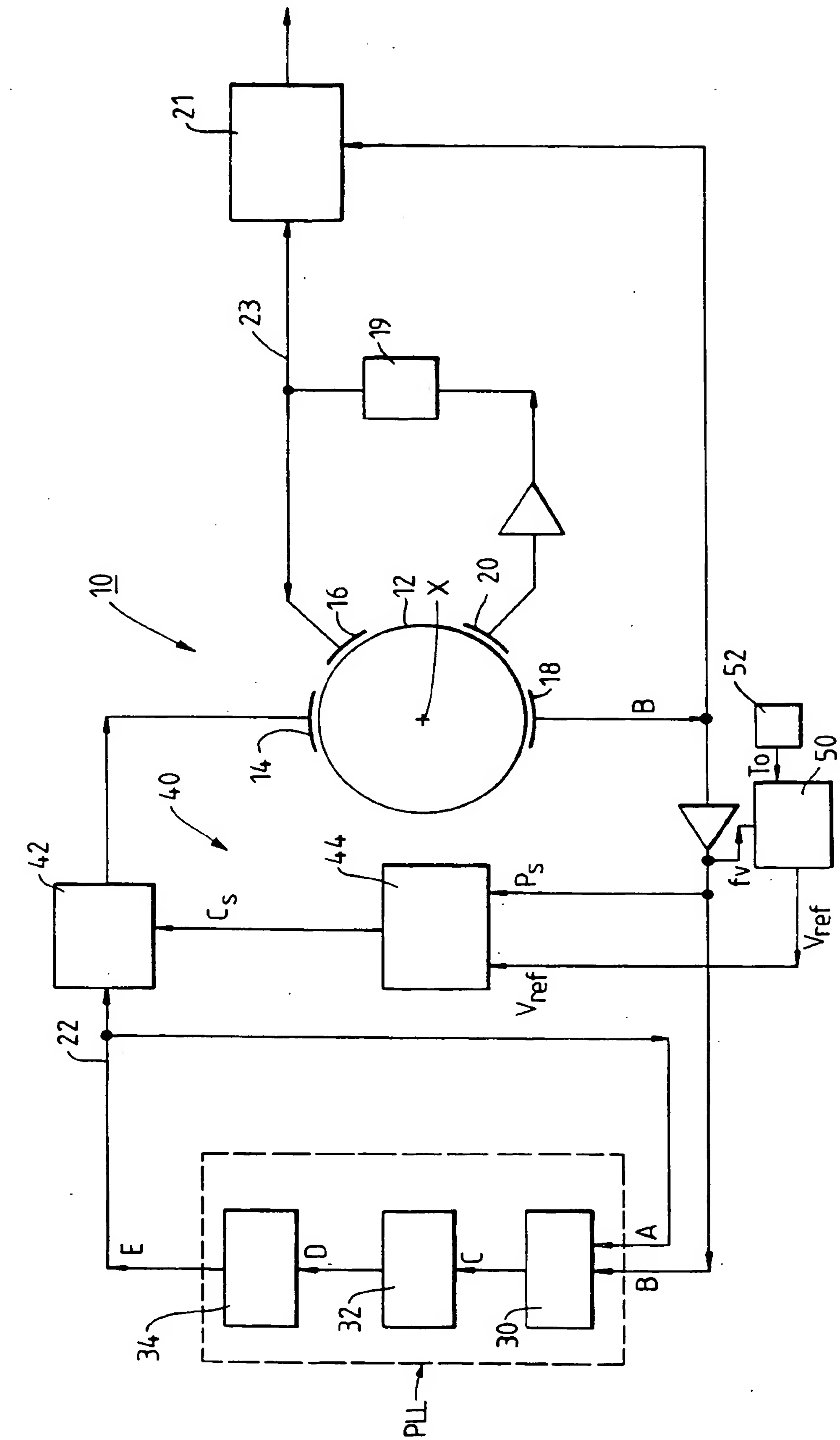


Fig. 4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PLL
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To

Fig. 5.

Fig.6

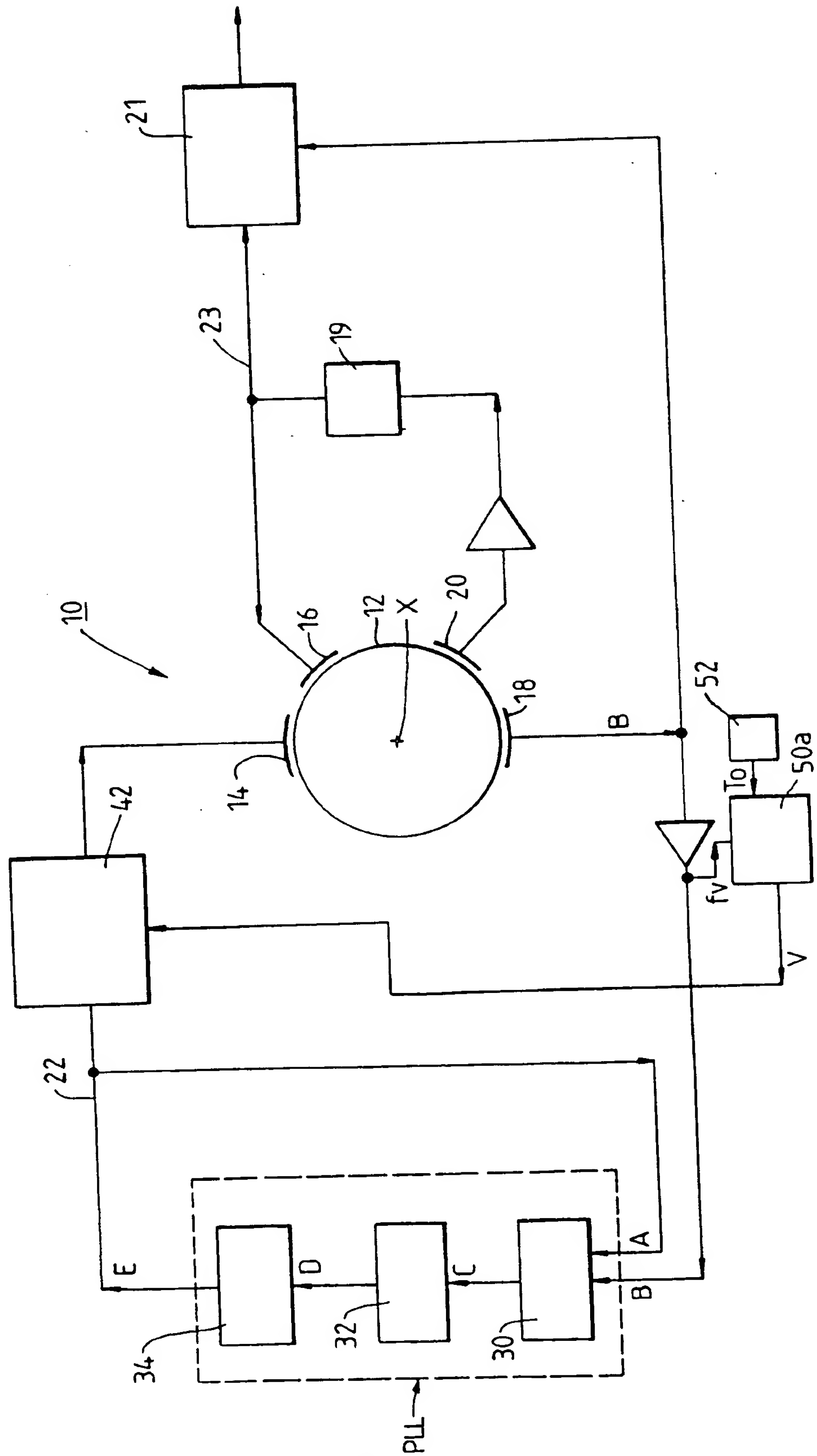

Fig. 7

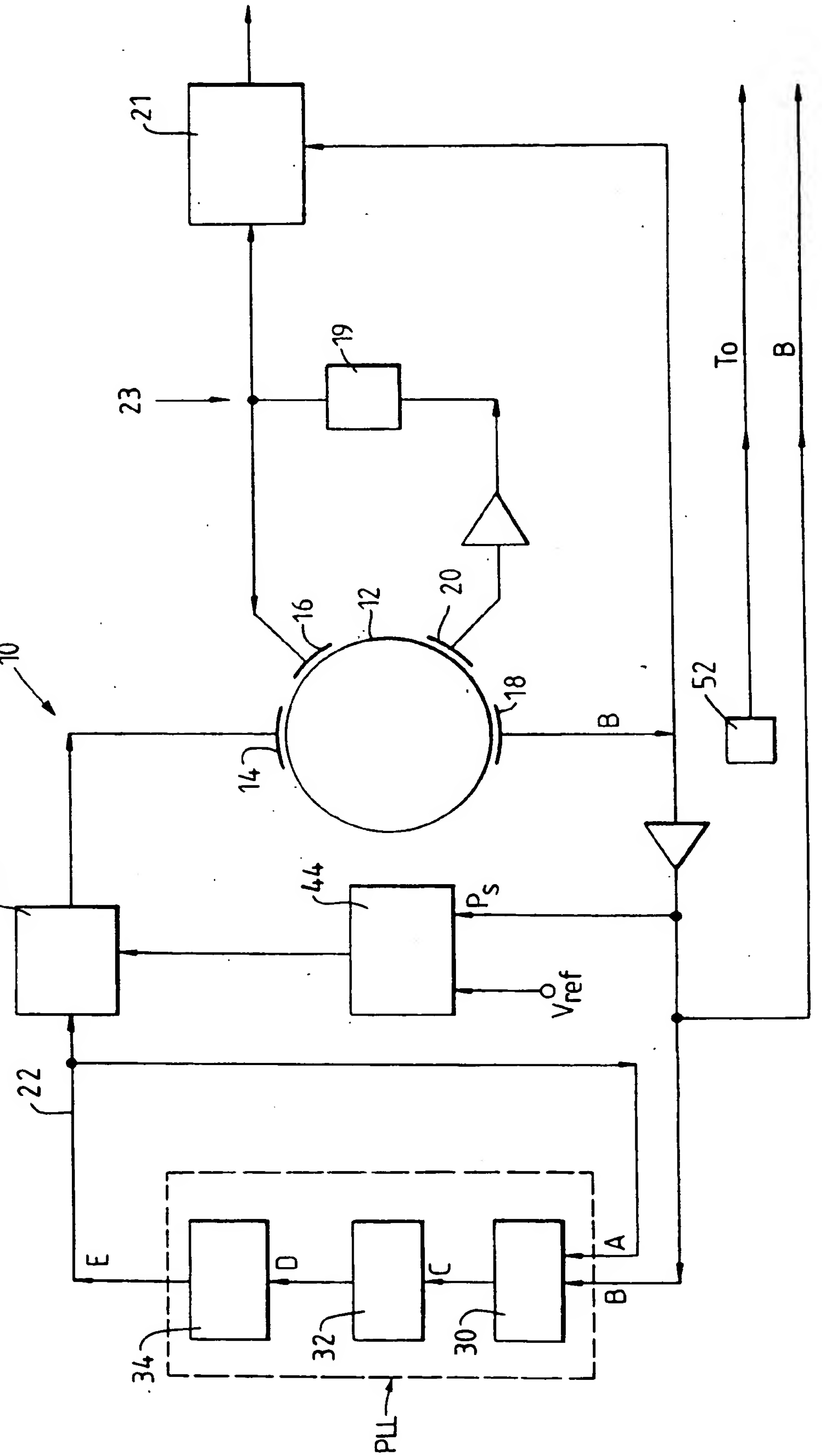

Fig. 8

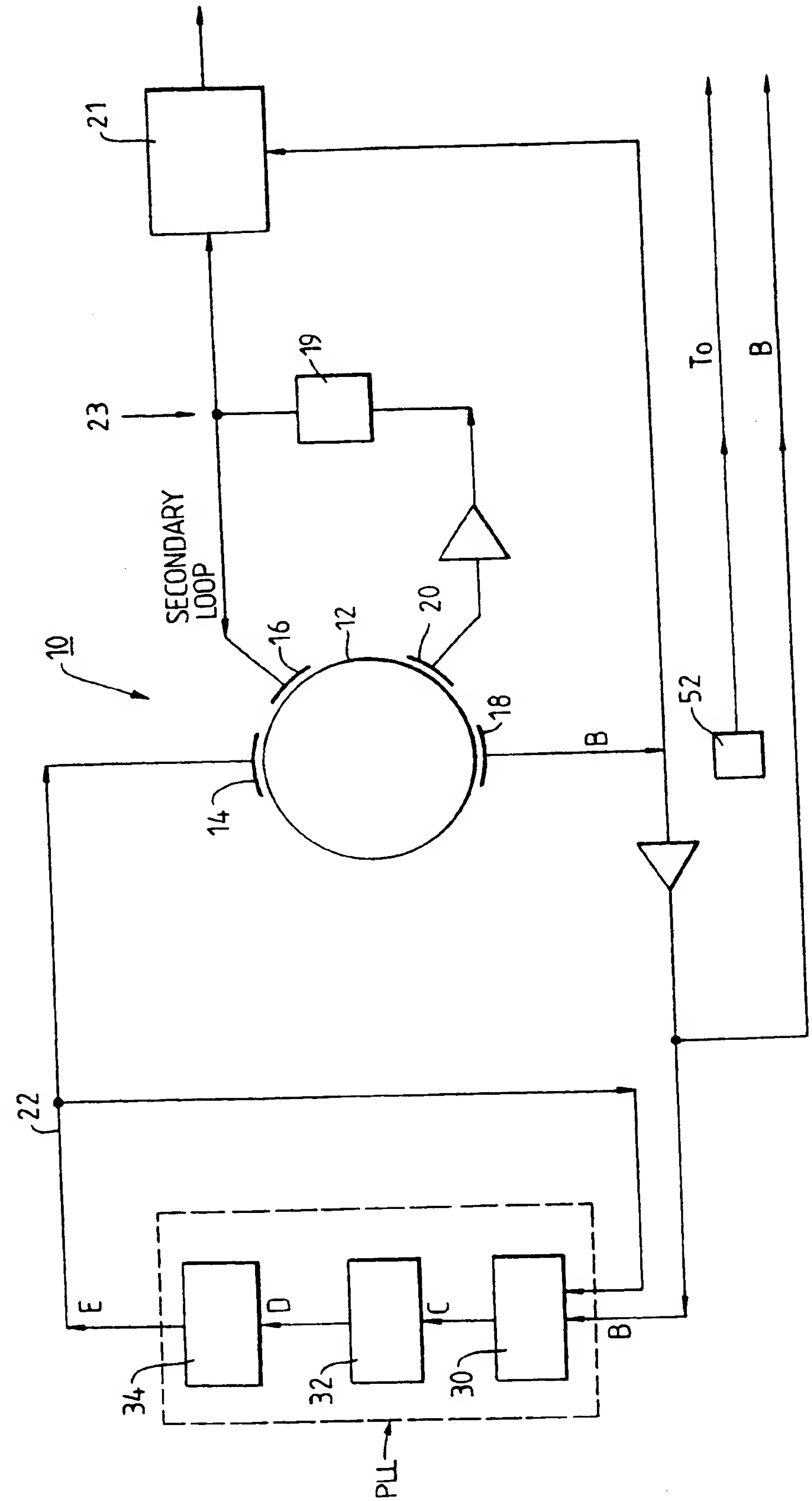
21
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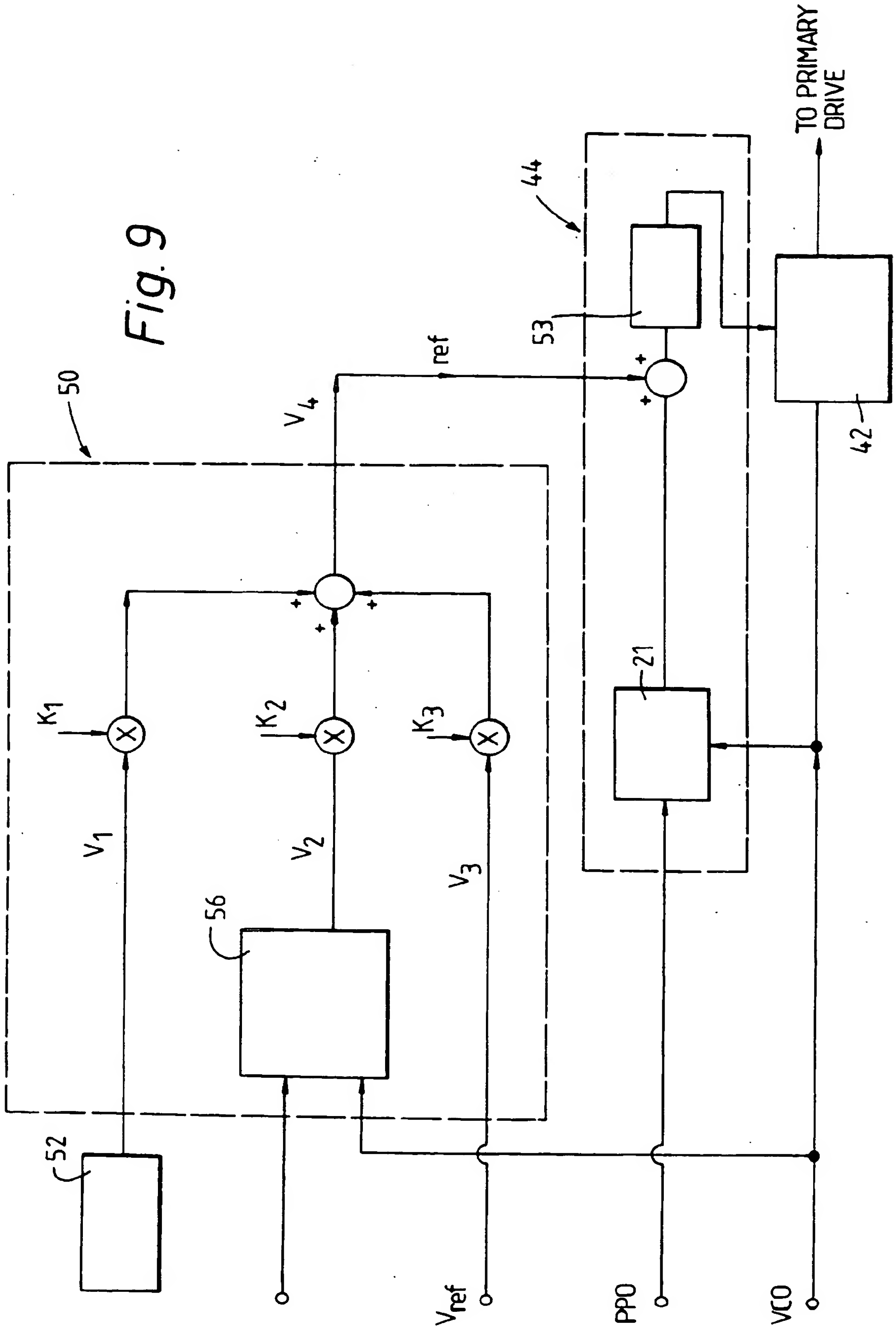
Fig. 9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Application Number
EP 93 30 7867

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.5)
A D	EP-A-0 153 189 (NATIONAL RESEARCH DEVELOPMENT CORPORATION) * page 2, line 32 - page 3, line 31; figures 1,6 * & GB-A-2 154 739 (NATIONAL RESEARCH DEV. CORP.) ---	1-3,10	G01P1/00 G01C19/56
A	EP-A-0 492 739 (BRITISH AEROSPACE PUBLIC LTD. COMP.) * column 1, line 21 - line 47; figure 4 * ---	1	
A,D	GB-A-2 061 502 (THE MARCONI COMPANY LIMITED) * page 1, line 22 - line 101 * * page 2, line 53 - line 67; figures 1,3 * -----	1,3,9,10	

TECHNICAL FIELDS SEARCHED (Int.Cl.5)

G01P
G01C

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	11 January 1994	Hansen, P

CATEGORY OF CITED DOCUMENTS

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